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Mechanisms to create high performance pseudo-ductile composites

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Abstract. Current composites normally fail suddenly and catastrophically, which is an undesirable characteristic for many applications. This paper describes work as part of the High Performance Ductile Composite Technology programme (HiPerDuCT) on mechanisms to overcome this key limitation and introduce pseudo-ductility into the failure process.

1. Introduction

Composite materials have excellent specific strength and stiffness, but a major drawback is their lack of ductility. The HiPerDuCT programme is a collaboration between the University of Bristol and Imperial College to address this challenge by developing new materials and architectures that give a more gradual failure.

Fibre reinforced composite materials normally exhibit sudden brittle failure, with linear elastic response to failure. Although some analyses have suggested the possibility of gradual degradation as a result of successive ply failures, such behavior is rarely observed experimentally, and failure is normally catastrophic, with little warning.

Ideally, ductile failure is desirable, with no loss of modulus on reloading. A more achievable target using currently available materials is pseudo-ductility, where non-linearity or “pseudo-yielding” is achieved via damage. Although this results in a loss of modulus on reloading, it still allows load redistribution around stress concentrations, potentially making the material less notch sensitive and more damage tolerant. A long, flat plateau is desirable, preferably with a positive “work hardening” slope to avoid localization of failure.

Three fundamental mechanisms are considered in this paper which enable pseudo-ductility under tensile loading: fibre reorientation, hybridisation, and interfacial slip in discontinuous fibre composites. Pseudo-ductile strain has been proposed as a key measure to assess progress, defined as the difference between the final failure strain, and the elastic strain at the same stress based on the initial modulus E_0 , figure 1. In some cases a sharp “yield” point is observed, but in others there is a gradual non-linearity. To account for this, the stress σ_y at an offset “plastic strain” ϵ_p is used, analogous to the proof stress in metals, with corresponding pseudo-yield strain ϵ_y .

Design strains would be expected to be within the initial linear region to avoid issues with fatigue, with the pseudo-yielding catering for overloads and localized damage and stress concentrations. Although the pseudo-yield strains are lower than the ultimate failure strains of the baseline materials, they are still potentially higher than current design strains which are very low due to concerns about brittle failure, and issues such as notched strength and impact.



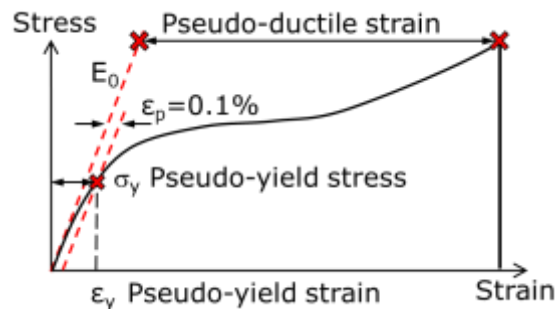


Figure 1. Definition of pseudo-ductile strain

2. Ductility via fibre re-orientation

It has been successfully demonstrated that using Skyflex carbon/epoxy plies of only 0.03 mm thickness, matrix cracking and delamination can be completely suppressed in angle-ply laminates, allowing the fibres to rotate under tensile loading, creating additional strain and pseudo-ductility [1]. Angle plies of (± 45) layup can produce strains of over 20% and necking behaviour despite the brittle nature of the matrix (see figure 2). There is a trade-off between the stresses and strains that can be achieved depending on the angle, and this has been investigated in modelling studies [2]. A good balance of properties has been achieved for example with thin ply (± 25) carbon/epoxy laminates that gave a pseudo-ductile strain of 1.23% and a maximum stress of 927 MPa, figure 3 [1].

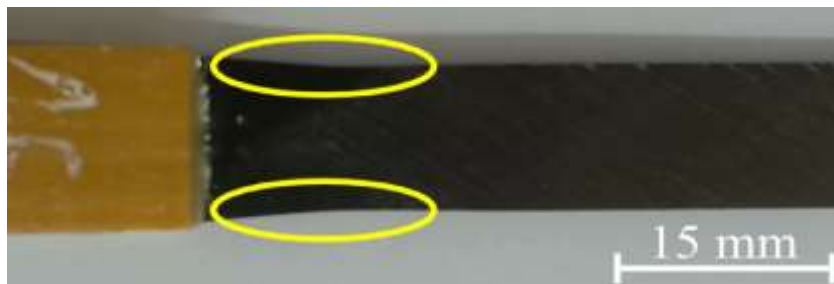


Figure 2. Necking of (± 45) thin ply carbon/epoxy angle ply specimen

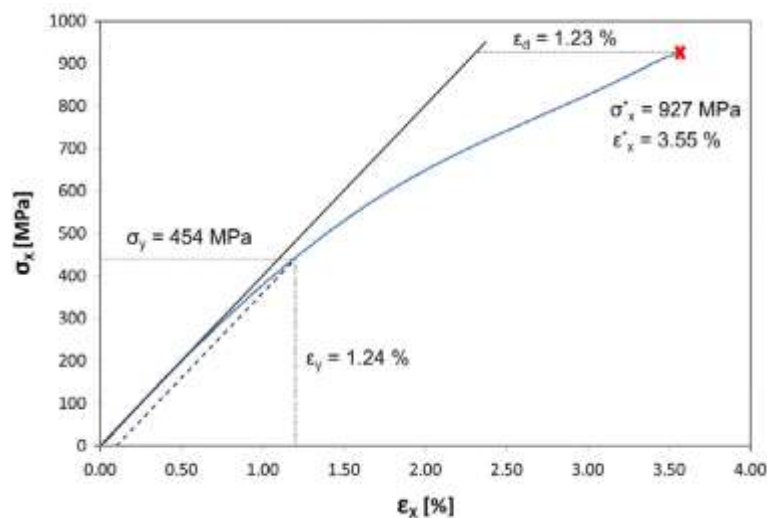


Figure 3. Pseudo-ductile response of thin ply (± 25) carbon/epoxy laminate

Tests involving loading, unloading and then reloading have shown that the initial modulus is fully recovered, and so these laminates may be considered as ductile rather than pseudo-ductile, figure 4 [3].

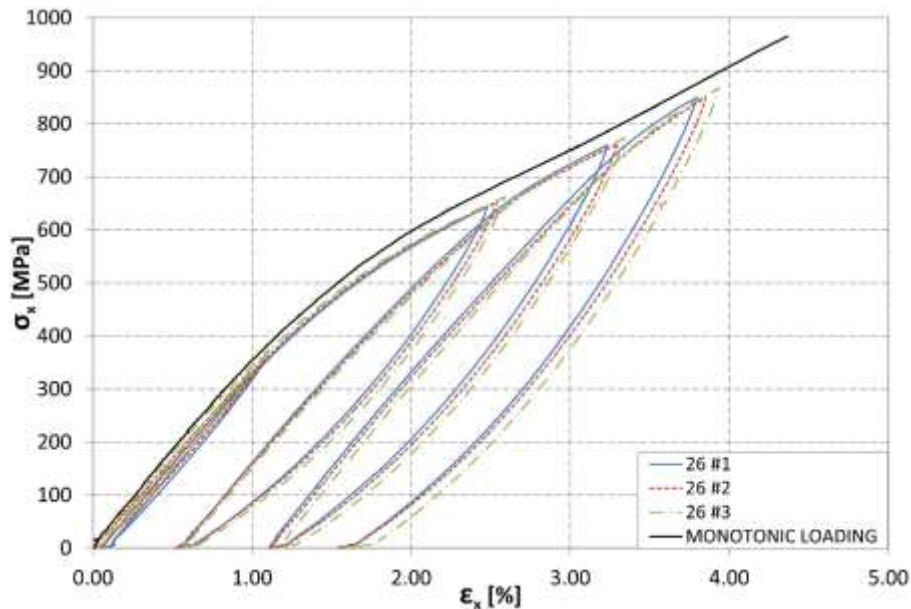


Figure 4. Cyclic loading of $(\pm 26)_s$ carbon/epoxy laminate

3. Ductility via fragmentation in thin-ply hybrids

Suppressing delamination in hybrid laminates can also be achieved by using thin plies [4]. Modelling has shown that both the relative thickness (i.e. proportion of carbon) and absolute thickness of the carbon plies are important [5-7]. Damage mode maps can be produced such as Figure 5, with the different failure mode regions in this case indicated approximately based on FE analysis [5]. However analytical models allow the boundaries to be calculated explicitly [6]. With the correct thicknesses, premature brittle failure of the whole hybrid plate and catastrophic delamination can be avoided. This leads to the new failure mechanisms of fragmentation of the stiffer ply, and stable pull-out of the fragments,

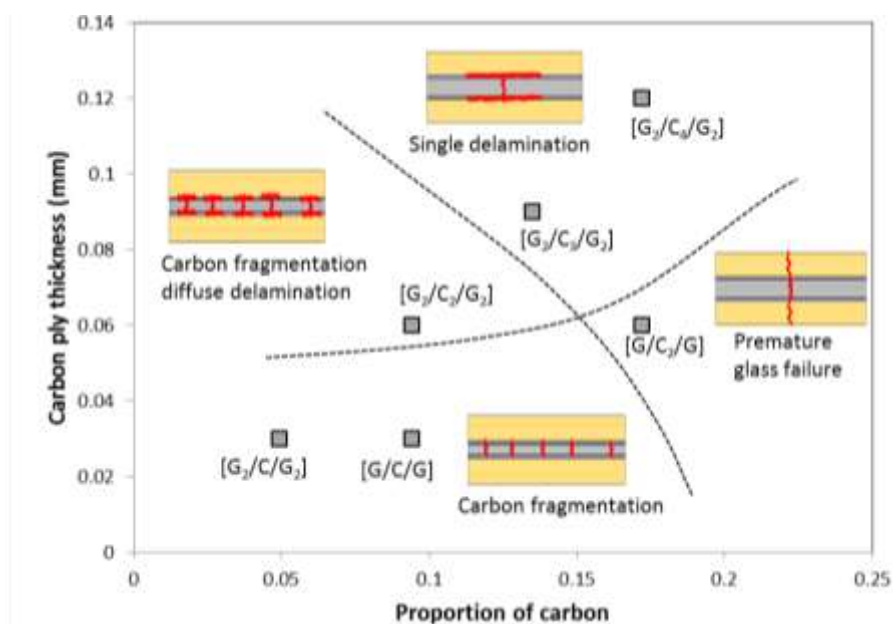


Figure 5. Damage mode map for E glass/thin carbon hybrid composite [5]

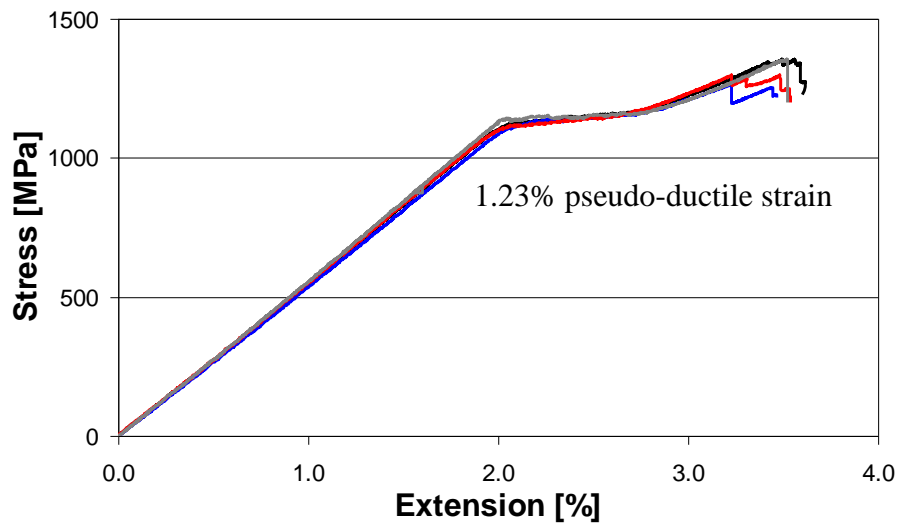


Figure 6. Pseudo-ductile response of S-glass/high strength carbon hybrid [8]

producing a pseudo-ductile stress-strain response. There is a trade-off between pseudo-ductility and yield stress. Figure 6 shows a typical response for two 21 g/m² plies of high strength TR30 carbon sandwiched between single 190 g/m² S-glass epoxy plies on either side. A range of different glass-carbon hybrid configurations has been evaluated, and pseudo-ductile strains of up to 2.66% have been obtained with a plateau stress of 520 MPa, or 0.86% pseudo-ductile strain with a plateau stress of over 1300 MPa [8].

Similarly pseudo-ductile response has been demonstrated with hybrids with different grades of carbon fibres. Figure 7 shows the response of hybrid specimens made from thin plies of Granoc XN80 ultra-high modulus carbon between layers of T1000 intermediate modulus carbon fibres, both preregs supplied by North Thin Ply Technology [9]. It has also been shown that pseudo-ductile behaviour is obtained with quasi-isotropic laminates made from similar unidirectional carbon fibre hybrid sub-laminates [10].

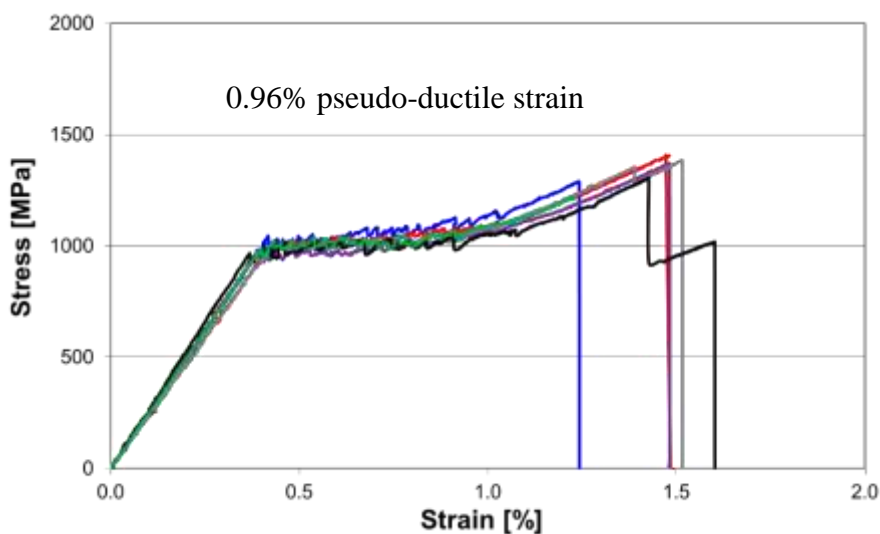


Figure 7. Stress-strain response for [T1000₂/XN80₂/T1000₂] carbon hybrid

Damage mechanisms have been investigated and it has been shown that acoustic emission can be used to detect fragmentation, with a direct correlation between acoustic emission and fragmentation events, allowing the technique to be used to detect fragmentation in opaque carbon/epoxy laminates [11].

Loading-unloading-reloading tests show a reduction in initial modulus due to the damage, and so these laminates do not show true ductility [12].

When the low strain plies in the hybrid laminates are very thin, there is an enhancement in the strain to failure due to the hybrid effect [13]. This only occurs for plies less than 0.1 mm thick, and can be as high as 20% for a single ply 0.03 mm thick. This effect can be modelled, and has been shown to be due to the constraint on forming critical clusters of fibre breaks [13]. This means that as well as producing pseudo-ductile response, these hybrid laminates are able to take greater advantage of the intrinsic properties of the carbon fibres.

Initially it was thought that this mechanism would only be operative in tension, but it has been found that fragmentation also occurs in thin ply M55 carbon/ S glass laminates in compression on the surface of specimens loaded in bending [14]. The carbon fibres fracture, and then some relative movement between the fracture surfaces allows further loading and fracture elsewhere, leading to a similar fragmentation behaviour and associated change in stiffness to that observed in tension.

4. Ductility via fragmentation in thin angle plies with 0° plies

The two previous mechanisms can be combined by replacing the lower modulus glass plies in a glass/carbon hybrid with carbon fibre angle plies [15]. This allows the fragmentation mechanism exhibited by the unidirectional hybrid composites to occur in the 0° plies together with the fibre rotation of the angle plies. For example $[\pm 26_s/0]_s$ laminates of Skyflex thin carbon/epoxy gave the response shown in figure 8, with a pseudo-ductile strain of 2.2%. On reloading, these laminates do show some loss of initial modulus due to the fragmentation of the 0° plies, and so are pseudo-ductile [3].

Different materials can be used for the 0° and angle plies. For example a (25/-25/0/-25/25) layup using thin ultra-high modulus carbon for the 0° ply but standard modulus thin carbon for the angle plies allows a pseudo-ductile sub-laminate to be produced which is only 0.15 mm thick and has a modulus of 135 GPa [16].

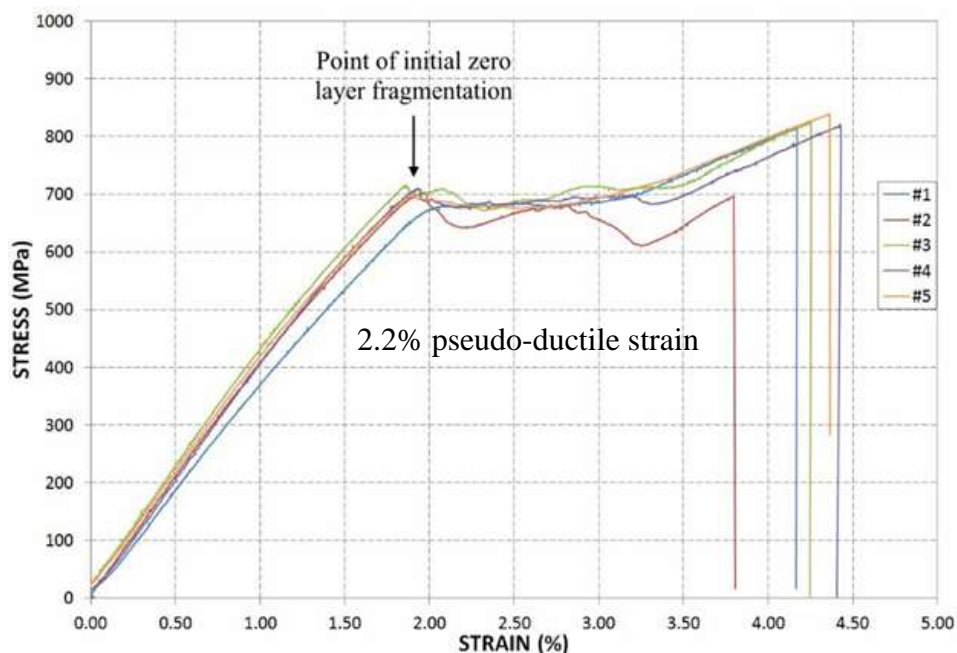


Figure 8. Pseudo-ductile response of $[\pm 26_s/0]_s$ laminate

5. Ductility in discontinuous fibre composites

Another mechanism for pseudo-ductility is slip at the interfaces between discontinuous fibres or plies. This has been demonstrated in model systems of discontinuous carbon/epoxy prepreg where the plies have been cut through the thickness prior to layup. The effect of ply thickness, cut spacing and alignment on the response have been investigated both numerically and experimentally [17]. For example specimens of IM7/8552 carbon/epoxy with 0.25 mm thick discontinuous ply blocks (0.125 mm for surface plies) and overlap length of about 8 mm were tested, (see figure 9). Significant non-linearity was obtained, providing a clear indication of damage, with a modest pseudo-ductile strain of 0.25%.

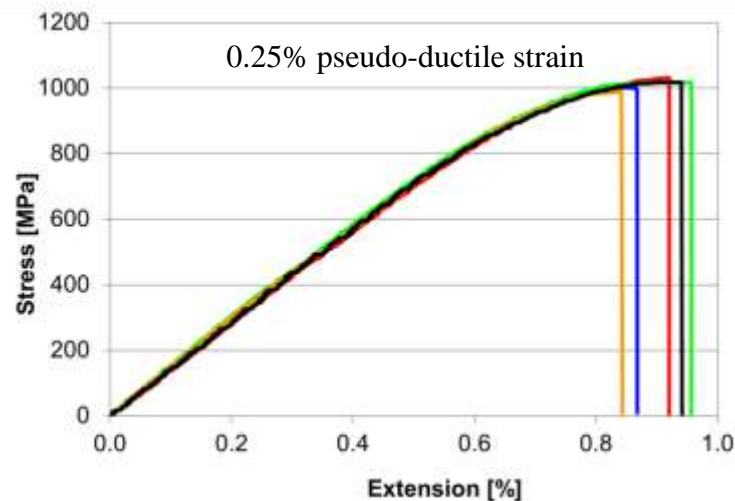


Figure 9. Non-linear response of discontinuous carbon/epoxy laminate

Non-linear tensile behaviour can also be produced in short fibre composites. The HiPerDiF method allows manufacture of high volume fraction well aligned unidirectional short fibre composites [18]. When high-modulus carbon and glass fibres are mixed, non-linear response and pseudo-ductility can be obtained similar to that achieved with thin plies. For example different relative volume fractions of Granoc XN90 ultra-high modulus carbon and E-glass fibres produce the stress-strain responses shown in figure 10 [19], with the relative carbon ratio indicating the volume of carbon compared with the total fibre volume.

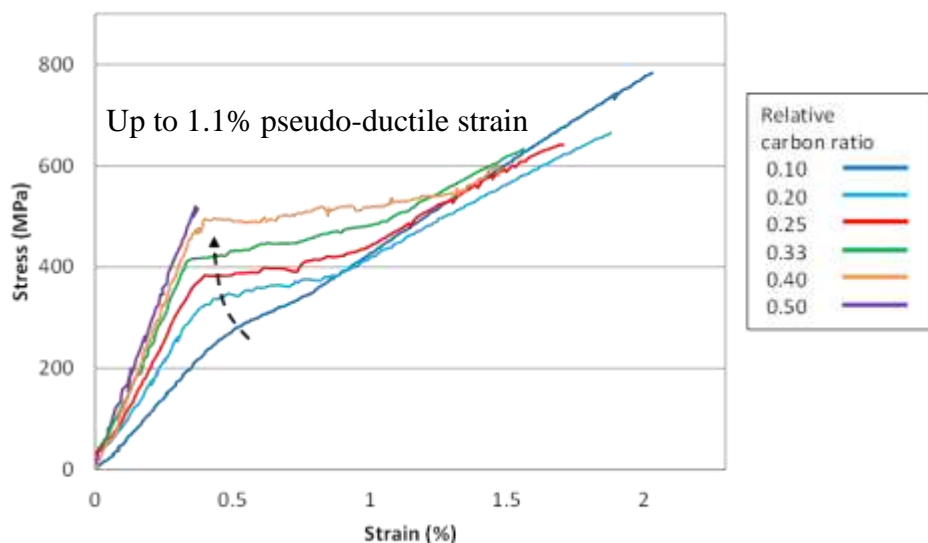


Figure 10. Non-linear response of hybrid XN90/E-glass short fibre composites

In this case the non-linearity is due to fragmentation, and the mechanism is similar to that obtained with hybrid laminates, but at the fibre rather than ply scale. However if the fibres are shorter than the critical length, a different mechanism occurs, with slip between fibres, similar to the behaviour demonstrated with the discontinuous prepreg. For example well aligned composites with 3 mm long standard modulus carbon fibres (C124, Toho Tenax) have been produced with a polypropylene matrix. These materials give the response shown in figure 11 [20]. Whilst there is some non-linearity, the amount of pseudo-ductility is modest, and the composite tends to fail at a relatively low strain due to localisation.

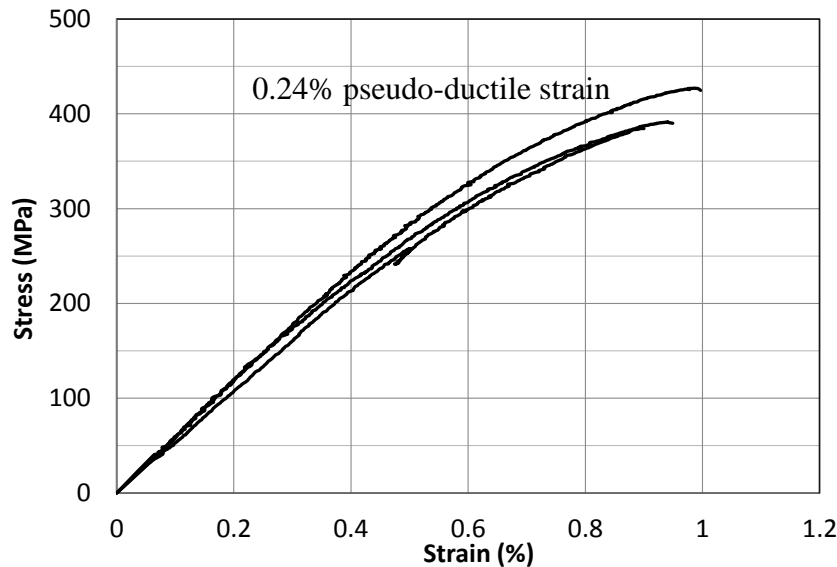


Figure 11. Non-linear response of short carbon fibre/polypropylene composite

6. Notched response of pseudo-ductile composites

The pseudo-ductility produced due to fragmentation and the associated non-linear response should allow load redistribution to occur at stress concentrations, resulting in notch-insensitive response, in a similar way to stress redistribution due to plasticity in ductile metals. To investigate this, notched quasi-isotropic pseudo-ductile laminates made from T1000/XN80 hybrid carbon sub-laminates similar to the unnotched unidirectional specimens presented in section 3 were tested [10]. Specimens 16 mm wide with 3.2 mm holes drilled were tested in open hole tension. Figure 12 shows the response, indicating that the

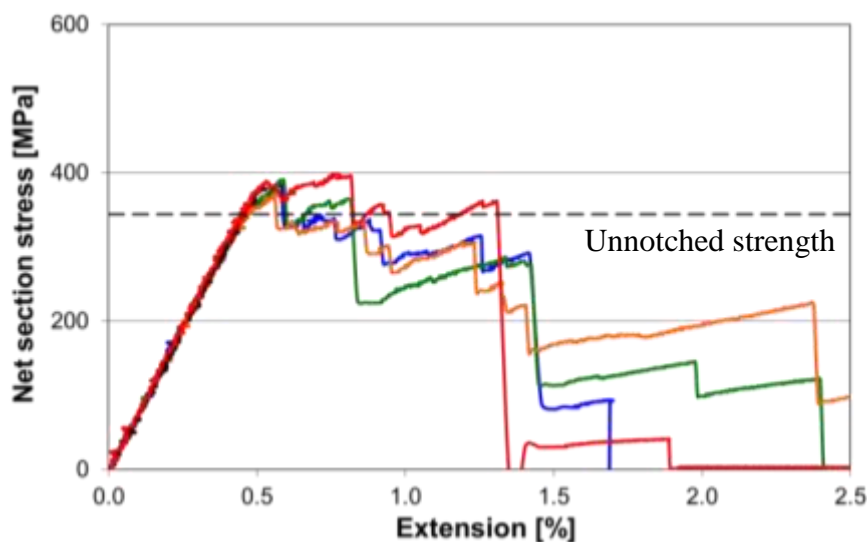


Figure 12. Open-hole tension of QI hybrid carbon specimens

specimens have actually exceeded the net section unnotched strength of the laminate, showing complete notch insensitivity. In addition, after the net section strength had been reached, they did not immediately fail catastrophically, but still showed some residual load carrying capacity, gradually reducing with further increasing strain.

Similarly modelling studies have shown that angle ply laminates with fragmenting 0° plies can also show notch insensitivity [21] and this has subsequently been demonstrated experimentally.

7. Conclusions

A number of different mechanisms have been demonstrated by which the sudden catastrophic failure of conventional composites in tension can be overcome, and a pseudo-ductile, gradual failure achieved. Using very thin plies can suppress matrix cracking and delamination, allowing fibre rotation and large strains to be obtained in angle-ply laminates. Thin ply hybrids can fail gradually by in-situ ply fragmentation. These mechanisms can be combined to produce laminates that demonstrate significant pseudo-ductile strain by both fragmentation and rotation. More limited pseudo-ductility has also been demonstrated with discontinuous carbon/epoxy plies and short fibres. Pseudo-ductile hybrid laminates have been shown to be notch insensitive. These results open up new possibilities for creating high performance composites that fail in a more gradual manner.

Acknowledgements

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